AL-TR-1993-0054

AD-A270 652

ARMSTRONG LABORATORY

A MULTIVARIATE ANTHROPOMETRIC METHOD FOR CREW STATION DESIGN (U)

Richard S. Meindl
Jeffrey A. Hudson

DEPARTMENT OF ANTHROPOLOGY AND
SCHOOL OF BIOMEDICAL SCIENCES
KENT STATE UNIVERSITY
KENT, OHIO

Gregory F. Zehner

CREW SYSTEMS DIRECTORATE
HUMAN ENGINEERING DIVISION
WRIGHT-PATTERSON AFB OH 45433-7022

FINAL REPORT FOR PERIOD JANUARY 1989-JANUARY 1993

MARCH 1993

Approved for public release; distribution is unlimited.

AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICES

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Please do not request copies of this report from the Armstrong Laboratory. Additional copies may be purchased from:

National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

Federal Government agencies and their contractors registered with the Defense Technical Information Center should direct requests for copies of this report to:

Defense Technical Information Center
Cameron Station
Alexandria, Virginia 22314

TECHNICAL REVIEW AND APPROVAL

AL-TR-1993-0054

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

KENNETH R. BOFF, Chief
Human Engineering Division
Armstrong Laboratory

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704 0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
MARCH 1993

3. REPORT TYPE AND DATES COVERED
Final Report Jan 1989 Jan 1993

4. TITLE AND SUBTITLE
A Multivariate Anthropometric Method
For Crew Station Design: Abridged

5. FUNDING NUMBERS
F 33615-85-C-0541
PE 62202 F
PR 7184
TA 08
WU DI

6. AUTHOR(S)
Gregory F. Zehner
Richard S. Meindl
Jeffery A. Hudson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Armstrong Laboratory, Crew Systems Directorate
HSC, AFMC Wright-Patterson AFB OH 45433-7022
Kent State Univ. Kent, Ohio 44242

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Armstrong Laboratory, Crew Systems Directorate
HSC, AFMC
Wright-Patterson AFB OH 45433-7022

10. SPONSORING MONITORING AGENCY REPORT NUMBER
AL-TR-1993-0054

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Body size accommodation in USAF cockpits is still a significant problem despite all the years of experience and the many aircraft designs that have been developed. Adequate reach to controls, body clearances (particularly during escape), and vision (internal and external), are all functions of pilot body size and position in the cockpit.

One of the roots of this problem is the way cockpit accommodation is specified and tested. For many years the percentile pilot has been used. This paper describes the errors inherent in the "percentile man" approach, and presents a multivariate alternative for describing the body size variability existing in a given flying population. A number of body size "representative cases" are calculated which, when used properly in specifying, designing, and testing new aircraft, should ensure the desired level of accommodation.

The approach can be adapted to provide anthropometric descriptions of body size variability for a great many designs or for computer models of the human body by altering the measurements of interest and/or selecting different data sets describing the anthropometry of a user population.

14. SUBJECT TERMS
Anthropometry Crew Station Design
Ergonomics Size

15. NUMBER OF PAGES
40

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540 01 280 5500

Standard Form 298 (Rev 2 89)
Prescribed by ANSI Std Z39-18
298-102

THIS PAGE LEFT BLANK INTENTIONALLY.

PREFACE

The authors would like to thank staff members at Anthropology Research Project, Inc. (ARP) for help in data preparation and analysis. Kathleen M. Robinette of AL/CFHD provided helpful criticism of this report in its earlier drafts.

Thanks go also to Ilse Tebbetts and Jennifer Schinhofen of ARP for editing this report and producing the final camera-ready copy.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (cont'd)

SUMMARY

Body size accommodation in USAF cockpits remains a significant problem despite the years of research and the many aircraft designs that have been developed. Adequate reach to controls, body clearances (particularly during escape), and vision (internal and external), are all functions of pilot body size and position in the cockpit.

Among the roots of the problem are the errors and limitations inherent in traditional approaches (such as percentiles) for specifying and testing cockpit accommodation. This paper describes a multivariate alternative for describing the body size variability existing in a given flying population. A number of body size "representative cases" are calculated which, when used properly in specifying, designing, and testing new aircraft, ensure the desired level of accommodation.

The approach can be adapted to provide anthropometric descriptions of body size variability for a great many designs or for computer models of the human body by altering the measurements of interest and/or selecting different data sets describing the anthropometry of a user population.

THIS PAGE LEFT BLANK INTENTIONALLY.

A MULTIVARIATE ANTHROPOMETRIC METHOD FOR CREW STATION DESIGN

INTRODUCTION

The recent development of computer models of the human body for describing dimensional variability of military personnel has advanced beyond current methods to describe and use available anthropometric data. In fact, anthropometric data are generally used to estimate only the extremes of univariate (single variable) distributions of a few gross dimensions, with little provision for individuals with unusual anthropometric proportions (Roebuck et al., 1975). Since extreme ratios (e.g. long buttock-knee length coupled with short sitting height) present the most difficult design problems for accommodation in workstations or for protective equipment, univariate percentile rankings for user populations are inappropriate, except for the most general description of international anthropometric variability.

Subgroup methods, which identify and select individuals atypical in combinations of two or more variables, partly address this issue. However, the severe sample truncations used in this method require initially massive data bases. This is especially true if subgroups are defined by the outermost regions of joint distributions of more than two variables.

Regression methods predict body proportions that are realistic as well as segment sizes that are additive (Robinette and McConville, 1981). These approaches require that one or two "key" dimensions be chosen as independent variables. Yet all human body measures are "free to vary" in an experimental sense, and therefore serve poorly as regressors. This problem can be particularly pronounced in those instances in which standard deviations from regression are large (or bivariate correlations are low). For example, the statistical assumptions necessary for the application of least-squares regression designs are approximated *poorly* in workstation dimension studies, owing to moderate intercorrelations (McConville et al., 1978), and *not at all* in the analysis of mask fit/seal accommodation, because the correlations among human facial measurements are extremely low. The typical results of these analyses are extreme values for the independent variables (regressors), and considerably less extreme values for the dependent variables (regressands) (those predicted).

THE MULTIVARIATE DESCRIPTION OF AN ANTHROPOMETRIC SAMPLE: METHODS

Workstation accommodation and the fitting of clothing or facial equipment present two fundamentally different design sequences. Sizing involves discrete categorization, whereas workstation design demands built-in interval adjustment to accommodate anthropometric variation. However, each requires a thorough knowledge of both the variability and the intercorrelations in linear dimensions of user populations. These dimensions include superior-inferior "lengths" (e.g. torso heights or extremity lengths); medial-lateral "breadths" (e.g. bideltoid breadth), and dorsal-ventral "depths" (e.g. chest depth).

Individual members of any population of workstation users will manifest considerable variation in their *combinations* of dimensions, quite apart from the variation that occurs along the simple spectrum connecting the "largest" to the "smallest" operator. For instance, the moderate correlation of functional reach and eye height/sitting indicate that operators at less than the 35th percentile for one variable, and simultaneously more than the 80th on the other,

are not uncommon. The importance of the multivariate nature of human morphometrics is illustrated through the calculations of proportions of an operator population disaccommodated when various pairs of variables are considered, in McConville et al., (1978). The mathematical model of bivariate normality is easily extended to the joint distributions of more than two variables. The geometric analogy of the equal-probability ellipse has its counterpart in multivariate space as well.

The higher-dimensioned analogue of the bivariate ellipse is the p-dimensional hyper-ellipsoid. The "average" individuals in a multivariately measured population, which like all cases occupy their own unique positions in p-dimensional space (based on their p physical measurements), are encompassed by the smallest hyper-ellipsoids. Atypically sized and proportioned individuals are contained only within the largest of these "shells." Selection of the "volume" of the concentric ellipsoids controls the percentage of the population that is included (fitted), and conversely the proportion excluded (disaccommodated).

Principal components analysis (PCA) describes the multivariate structure of a single population. It is a data reduction procedure that can greatly simplify the use of a test sample for accommodation or sizing/design studies by reducing the number of dimensions of a hyper-ellipsoid. PCA provides a solution to a specific kind of eigenproblem. The PCA solution comprises four elements, which have been used here to provide more efficient body size models:

(1) New linear combinations of the original p variables provide p orthogonal (mutually independent) principal components. Each of these explains different amounts of the original morphometric variation contained in the measurement space (Dillon and Goldstein, 1984). It is important to emphasize that this reduced measurement space is constructed of axes which exhibit no multicollinearity (i.e., these new axes show no correlation within the population). For instance, any two components, *i* and j, say,

$$PC_i = t_{i1} Z_1 + t_{i2} Z_2 + \ldots + t_{ip} Z_p$$

and

$$PC_j = t_{j1} Z_1 + t_{j2} Z_2 + \ldots + t_{jp} Z_p$$

in which the $(t_{i1}, t_{i2}, \ldots, t_{ip})$ represent loadings of the standardized variables $(Z_1, Z_2, \ldots, Z_p)$ on principal component i are orthogonal (i.e. completely uncorrelated in the population on which the components were derived).

Some of the new principal components represent major axes of variation, while some are much less important. Those principal components which account for minimal variation are discarded [i.e. nearly all of the original variation will fall approximately into a space, m (m < p), of reduced dimensionality].

(2) PCA may also reveal that some of the original variables are needless redundancies. The subsequent elimination of a variable can only be justified after its careful consideration as a trait

multivariate context -- that is, after understanding its simultaneous relationships with all other variables.

(3) Original measures may cluster into related morphometric classes. In other words, certain "families" of variables will tend to load more heavily on various components. These loadings are instructive to the principal components analyst as well as to the workstation designer and accommodation evaluator. They indicate the relationships between measures which represent the real dimensions of human metric variability.

(4) The principal components solution lends itself well to the determination of the volume and surface of the m-dimensional shells ($m < p$) that, with scale adjustment only, will encompass any given percentage of a multivariate population efficiently (see Figures 1 and 2; also see Bittner et al. (1986) for a useful outline of this procedure; Dillon and Goldstein (1984) provide a rationale).

This PCA-based numerical solution requires the following steps:

(1) Determination of the appropriate ellipsoidal accommodation "shell" (i.e. exact 95% or 98%). This is accomplished best by iteration. Since the anthropometric data are not exactly multivariate normal, simple adjustment of the sizes of the major axes by trial and error is most efficient.

(2) Solving for component scores that yield surface locations.

(3) Conversion of the surface points to standard normal scores according to the following series of matrix equations:

$$(a_{ij})\ (U) = (Z_i)/C$$

in which the a_{ij} constitute the p by m matrix of Pearson correlations of original variables with new components. U is one of the 2^m (m x 1) unit vectors of the form (± 1, ± 1, ± 1, . . .). For example, in a three-component solution the U represents each of the 8 ($=2^3$) possible unique combinations of three unit measures of different signs (± 1, ± 1, ± 1). This is explained in more detail in the section entitled "A Three-Component Model: A Combiman Application" on page 13. The $(Z_i)/C$ are (p x 1) vectors of standard normal scores divided by the constant, C, which is the common component score obtained in (2) above. The value of C sets the size of the ellipsoid of accommodation.

(4) These standard normal scores (Z_i), in turn, provide univariate percentile rankings (under the assumption of approximate normality) for each measure at each of the surface locations. This

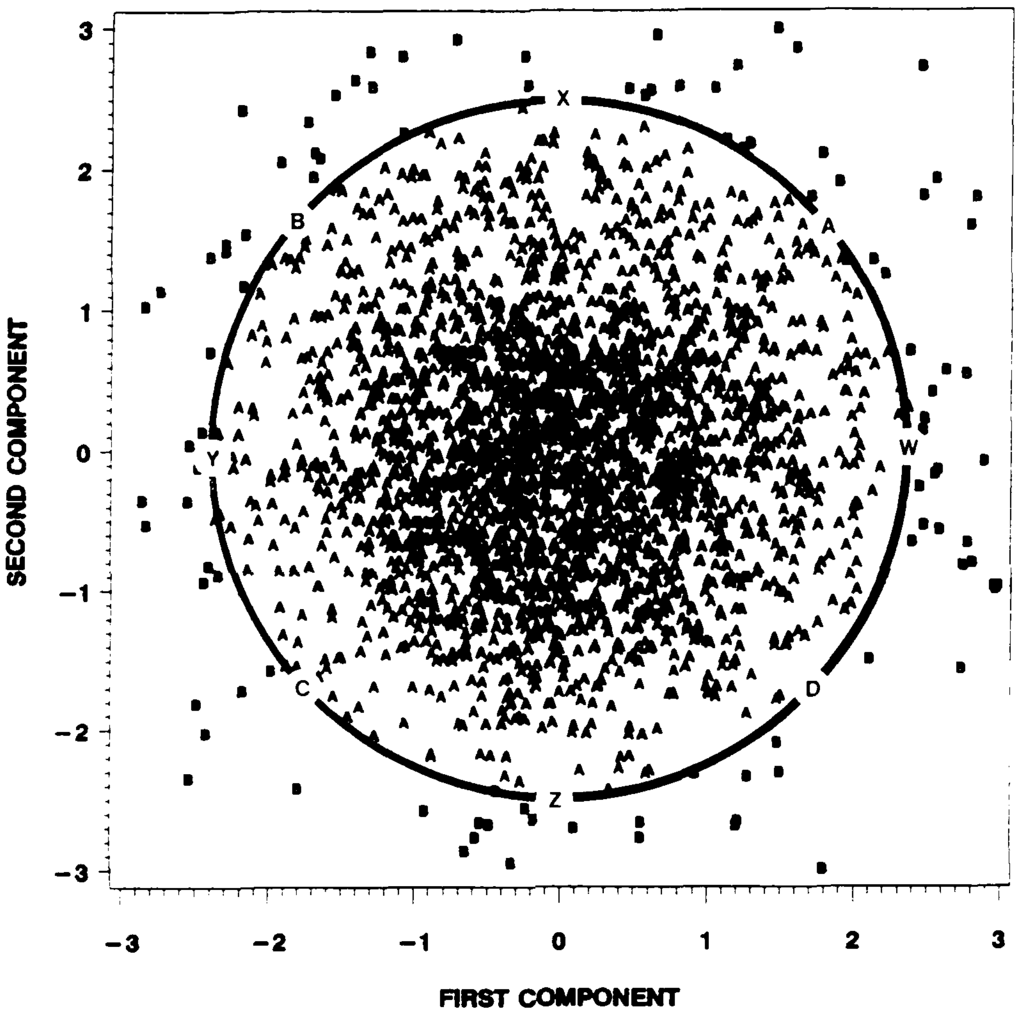

FIGURE 1

Principal Components Analysis: 95% Accommodation

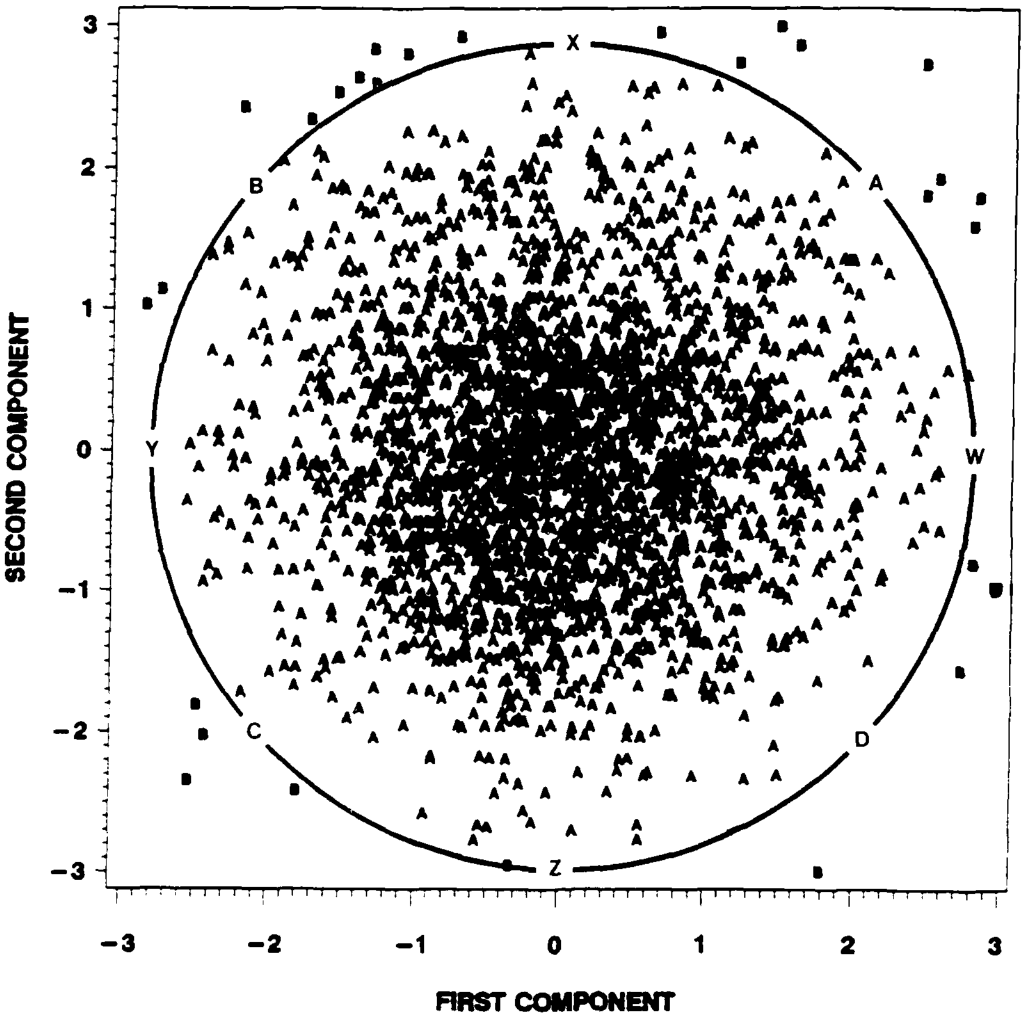

FIGURE 2

Principal Components Analysis: 98% Accommodation

procedure may be repeated for any other accommodation "shell" simply by varying C.

(5) Actual raw scores are then taken from the finite distributions of the population. These are calculated for the 95% accommodation ellipsoid, for the 98% ellipsoid, or for any other accommodation percentage required.

The test points on each of the concentric ellipsoids represent *extreme* individuals. Any accommodation "surface" contains special extreme cases which are situated symmetrically from the median operator (i.e., that "average" individual who may be best characterized as the arithmetic mean of all the variables). For instance, in a three-component example, the extreme individuals are positioned exactly at the midsurfaces of each of the eight octants of each accommodation ellipsoid (see Figure 3). Therefore, the design of any workstation, *which is compatible with these extreme individuals* should also accommodate all of the individuals who are closer to the multivariate mean. Computer models of Air Force personnel (e.g. Combiman or Crew Chief) can utilize these multivariate locations to test the limits of accommodation with more efficiency.

Models of anthropometric variability for aircraft cockpit dimensions were developed through principal components analyses designed to characterize the Air Force flying population. Various combinations of the linear dimensions were examined and user populations of different compositions were utilized. The ultimate selection of variable sets followed the consideration of several important criteria: (1) the direct relevance of the body dimension to the principal user/equipment *interfaces*; (2) the degree of *variability* in the measure; and (3) the amount of *independent* information contained in the variables (i.e. those with moderate to low covariance with other variables). Two types of rigid (orthogonal) principal components solutions (unrotated and varimax) following the initial generation of eigenvectors were explored.

ANALYSIS OF A TWO-COMPONENT MODEL

Bittner concluded in his analysis of the anthropometric compatibility for the Advanced Harrier (AV-16A) that leg and arm reach elements as well as head clearance were by far the most critical dimensions (Bittner, 1975). Therefore, any analysis which includes other metrics may obscure or confound these aspects of workstation design. For this reason we provide a simple description of the population of U.S. Air Force flying personnel (USAF67) to emphasize only superior-inferior linear dimensions.

The variable "functional reach" (thumb-tip reach, not extended) is used as the sole measure of the forelimb dimension, a measurement critical to cockpit design (the actual position of the elbow in this extension is of little importance). The actual position of the knee, as well as the individual thigh and shank lengths, are crucial, however, and in the following analysis both elements of the leg are retained (buttock-knee length and knee height/sitting). Trunk height is measured three different ways, from the seat pan to one of three superior levels: shoulder (acromion height sitting), eye level (eye height/sitting), and total axial frame (sitting height). The intercorrelation matrix of these six variables for USAF67 is given in Table 1.

It is not surprising that the principal components analysis of this correlation matrix reveals only two major components ($p=6$, $m=2$): These two (Table 1) account for 85% of the

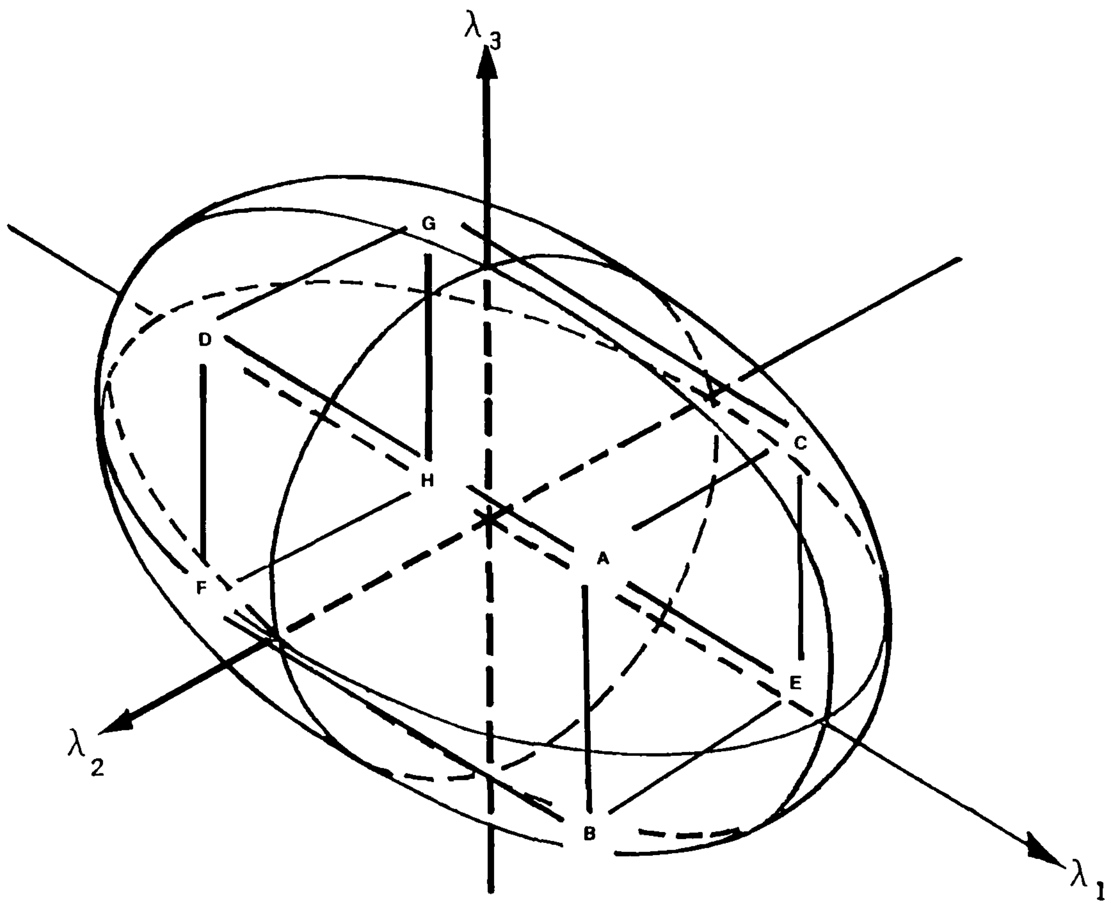

FIGURE 3

Three-Dimensional Principal Components Solution

TABLE 1

Six Anthropometric Variables Reduced to Two Principal Components, 1967 Air Force Flying Personnel

Correlation Matrix (r_{ij}):

		(1)	(2)	(3)	(4)	(5)
Thumb Tip Reach	(1)					
Buttock Knee Length	(2)	.61				
Knee Height/Sitting	(3)	.70	.78			
Sitting Height	(4)	.41	.39	.52		
Acromion Height/Sitting	(5)	.35	.34	.45	.81	
Eye Height/Sitting	(6)	.39	.39	.49	.93	.78

SUMMARY STATISTICS			FACTOR CORRELATION MATRIX:	
Variable	Mean (mm)	Std Dev (mm)	Factor 1	Factor 2
Thumb Tip Reach	803.1	39.8	.70574	.48318
Buttock Knee Length	604.0	27.0	.71883	.53912
Knee Height/Sitting	557.6	25.0	.81604	.44714
Sitting Height	931.8	31.8	.87047	-.42424
Acromion Height/Sitting	610.3	28.5	.79541	-.44823
Eye Height/Sitting	809.5	30.2	.85280	-.43105

Eigenvalues, (Unrotated Principal Components, λ_i) and Percentage of Variation (%):

Factors

	(1)	(2)	(3)	(4)	(5)	(6)
Eigenvalues	3.80	1.29	0.41	0.25	0.19	0.07
Variation	63%	22%	7%	4%	3%	1%

original variation, and the remaining four components play no subsequent role in the analysis. Both principal components are easily interpreted. The first appears to be a size component which describes nearly two-thirds of the original variation. The second is bipolar and may be described as extremity length relative to trunk height. Within-trunk correlations are quite high as are the within-limb correlations; however, between these groups of variables the correlations are very low.

The 95% and 98% accommodation limits for this model are shown in Figures 1 and 2. Eight surface points are indicated for each, and these are translated into their corresponding multivariate vectors in Tables 2 and 3. The locations are each symmetric about the centroid and, in terms of the component space (characterized by the ratio of $\lambda 1$ to λ_2), are equidistant from that point.

The interpretation of the eight surface points shown on Figure 1 is as follows: The first component (horizontal scale) is overall body size. In this respect, point Y is the smallest and W is the largest. The second component (vertical scale) represents contrasting limb/torso proportions. Both points Y and W have values of zero on this scale because they represent cases that show no contrast in limb/torso proportions -- that is, they are small or large on all measures. X and Z show the highest contrasts between limb and torso dimensions. X has long limbs combined with a short torso; Z has short limbs with a large torso. Each of these four cases are most extreme on one of the components but exactly average along the other. Cases B and C are also small for the first component (though not as small as Y) but show marked limb/torso contrast. Thus, while B is not as small *overall* as Y, this case has the smallest torso of the eight. Similarly, C is not as small overall as Y but exhibits the smallest limbs of the eight cases. Counterpart cases at the large end of the first component represent the same kinds of variability. A and D are not as large overall as W, but show the most extreme values for limbs and torsos, respectively. In a crewstation design each of these cases would adjust the seat and rudder carriage to different positions in the cockpit, and each case should be considered in order to represent the range of variability which exists in the population.

Deleting One Variable

The inclusion of as many as three trunk heights may prove to be somewhat redundant, resulting in an accommodation model which overly weights this aspect of flyer morphology. What is the effect of deleting a variable which is highly correlated with others? To examine this issue, an additional analysis was conducted which de-emphasizes trunk relative to the extremities by using only five of the six measures defined above: acromion height sitting was removed from the study. A comparison of these two analyses is instructive with regard to the impact of the addition/deletion of a single variable which may bring little additional information about morphology, since acromion height sitting correlates closely with total sitting height (r=.81) and also with eye height sitting (r=.78). See Table 1.

Both analyses share five variables as well as the same sample population; therefore, the correlation matrices are the same, save for the deletion of one row and column, which corresponds to the variable that was removed. The new analysis produced essentially two components (the last three are discarded). These account for 86.7% of the original variation in the five-variable system (compared to 84.8% of all variation in six-space in the first analysis). The two major components of the last analysis share the same interpretations as those of the first (compare Tables 1 and 4). All five variables are uniformly loaded on the large component,

TABLE 2

Accommodation Analysis, 95%, 1967 Air Force Flying Personnel:
Six Variables

Variable Z-Scores for "2-D Man" Model Points*

	A	B	C	D	W	X	Y	Z
Thumb Tip Reach	2.1	-0.4	-2.1	0.4	1.7	1.2	-1.7	-1.2
Buttock Knee Length	2.2	-0.3	-2.2	0.3	1.8	1.3	-1.8	-1.3
Knee Height/Sitting	2.2	-0.6	-2.2	0.6	2.0	1.1	-2.0	-1.1
Sitting Height	0.8	-2.3	-0.8	2.3	2.1	-1.0	-2.1	1.0
Acromion Height/Sitting	0.6	-2.2	-0.6	2.2	2.0	-1.1	-2.0	1.1
Eye Height/Sitting	0.7	-2.2	-0.7	2.2	2.1	-1.1	-2.1	1.1

Variable Values (mm) for "2-D Man" Model Points*

	A	B	C	D	W	X	Y	Z
Thumb Tip Reach	885.4	787.7	720.8	818.5	872.2	850.4	734.0	755.8
Buttock Knee Length	663.2	595.6	544.9	612.5	651.8	639.9	556.2	568.2
Knee Height/Sitting	612.5	541.6	502.8	573.7	607.7	585.1	507.6	530.2
Sitting Height	956.5	860.3	907.2	1003.4	999.9	898.7	863.8	965.0
Acromion Height/Sitting	627.8	548.8	593.3	672.3	666.4	579.1	554.7	642.0
Eye Height/Sitting	831.6	742.1	787.4	876.9	872.8	777.5	746.2	841.5

* Locations A, B, C, and D are each midquadrant points; W, X, Y, and Z refer to the points on the principal components axes.

TABLE 3

Accommodation Analysis, 98%, 1967 Air Force Flying Personnel:
Six Variables

Variable Z-Scores for "2-D Man" Model Points*

	A	B	C	D	W	X	Y	Z
Thumb Tip Reach	2.4	-0.5	-2.4	0.5	2.0	1.4	-2.0	-1.4
Buttock Knee Length	2.6	-0.4	-2.6	0.4	2.1	1.6	-2.1	-1.6
Knee Height/Sitting	2.6	-0.8	-2.6	0.8	2.4	1.3	-2.4	-1.3
Sitting Height	0.9	-2.7	-0.9	2.7	2.5	-1.2	-2.5	1.2
Acromion Height/Sitting	0.7	-2.6	-0.7	2.6	2.3	-1.3	-2.3	1.3
Eye Height/Sitting	0.9	-2.6	-0.9	2.6	2.5	-1.3	-2.5	1.3

Variable Values (mm) for "2-D Man" Model Points*

	A	B	C	D	W	X	Y	Z
Thumb Tip Reach	900.1	784.9	706.0	821.2	884.6	858.9	721.6	747.3
Buttock Knee Length	673.8	594.1	534.3	614.0	660.4	646.3	547.7	561.8
Knee Height/Sitting	622.3	538.8	493.0	576.5	616.7	590.0	498.6	525.3
Sitting Height	960.9	847.5	902.8	1016.2	1012.0	892.8	851.7	970.9
Acromion Height/Sitting	630.9	537.7	590.2	683.3	676.4	573.4	544.7	647.6
Eye Height/Sitting	835.6	730.1	783.4	888.9	884.1	771.8	734.9	847.2

* Locations A, B, C, and D are each midquadrant points; W, X, Y, and Z refer to the points on the principal components axes.

TABLE 4

Five Anthropometric Variables Reduced to Two Principal Components, 1967 Air Force Flying Personnel (Acromion Height/Sitting Deleted)

Correlation Matrix (r_{ij}):

		(1)	(2)	(3)	(4)
Thumb Tip Reach	(1)				
Buttock Knee Length	(2)	.61			
Knee Height/Sitting	(3)	.70	.78		
Sitting Height	(4)	.41	.39	.52	
Eye Height/Sitting	(5)	.39	.39	.49	.78

SUMMARY STATISTICS			FACTOR CORRELATION MATRIX	
Variable	Mean (mm)	Std Dev (mm)	Factor 1	Factor 2
Thumb Tip Reach	803.1	39.8	.76850	.37485
Buttock Knee Length	604.0	27.0	.78849	.43147
Knee Height/Sitting	557.6	25.0	.87191	.32528
Sitting Height	931.8	31.8	.80635	-.56141
Eye Height/Sitting	809.5	30.2	.79322	-.57891

Eigenvalues, (Unrotated Principal Components, λ_i) and Percentage of Variation (%):

Factors

	(1)	(2)	(3)	(4)	(5)
Eigenvalues	3.25	1.08	0.41	0.19	0.07
Variation	63%	22%	8%	4%	1%

which approximates "size," as before. The second component may also be labeled "extremity lengths relative to trunk." Here, the trunk variables load somewhat higher (compare Tables 1 and 4), and although there are now only two of five variables loading, compared to three of six in the earlier analysis, the second components are quite similar. The exact multivariate surface points are given in Tables 5 and 6.

The differences between the 5- and 6- component models generally are small (on the order of 3 to 4 mm), but occasionally show differences greater than 1 cm.

The eight test individuals for each accommodation surface are symmetric about the centroid (as described by the multivariate averages), and in terms of the component space, are equidistant from that operator. The design of any workstation which is compatible with these extreme individuals should also accommodate all of the cases which are less extreme. These analyses indicate that there exist perhaps no more than two important and independent superior-inferior components of variation in the flyer population for consideration of cockpit accommodations, that limb extremities tend to load together and quite equally on major components, and that the superior-inferior measurements of *trunk* and *limbs* are largely independent, apart from the usual allowance for overall body size.

A THREE-COMPONENT MODEL: A COMBIMAN APPLICATION

Eleven linear anthropometric dimensions which serve as input for the COMputerized BIomechanical MAN-Model (COMBIMAN) programs (Korna and McDaniel, 1985:95) were selected as a preliminary example ("weight" was not used; therefore, all utilized measures were in mm.). The United States Air Force 1967 Flying Personnel Survey sample (n = 2420) again provides an appropriate and sufficiently large sample so that anthropometric univariate distributions as well as their covariances may be regarded as accurate estimates, with very minimal sampling error. The amount of covariation in these data was quite large (i.e., the determinant of the correlation matrix = 6.4×10^{-4}) and a principal components analysis of this matrix provided a useful summary of the system.

Six components accounted for 90% of the variation, the vast majority of which (51%) was found along a single vector. This unipolar component correlated with, and represents, overall size of the individuals. A second orthogonal component was related to some of the cross sectional dimensions of the trunk. The third was related primarily to the superior-inferior dimensions of head, neck, and torso. The first six principal components were rotated using a varimax procedure. This resulted in a new and simpler set of coordinate axes, the first three of which (λ_1, λ_2, and λ_3) provide perhaps the best preliminary summary of the multivariate structure of the COMBIMAN metrics.

The components represent more relevant measures for workstation accommodation than do the variables themselves: the first axis (λ_1) represents limb elements; the second (λ_2), vertical dimensions of head, neck, and trunk; and the third (λ_3), hand and foot lengths. These are listed in descending order of variation explained; the remaining three components were discarded. The varimax procedure (Harman, 1975) resulted in a more spherical (i.e. less prolate) solution (Figure 3). The three rotated components accounted for 61% of the total original variation, and this amount was more evenly distributed among the three than was the case for the first three components in unrotated space.

TABLE 5

Accommodation Analysis, 95%, 1967 Air Force Flying Personnel:
Five Variables

Variable Z-Scores for "2-D Man" Model Points*

	A	B	C	D	W	X	Y	Z
Thumb Tip Reach	2.0	-0.7	-2.0	0.7	1.9	0.9	-1.9	-0.9
Buttock Knee Length	2.1	-0.6	-2.1	0.6	1.9	1.1	-1.9	-1.1
Knee Height/Sitting	2.1	-1.0	-2.1	1.0	2.2	0.8	-2.2	-0.8
Sitting Height	0.4	-2.4	-0.4	2.4	2.0	-1.4	-2.0	1.4
Eye Height/Sitting	0.4	-2.4	-0.4	2.4	2.0	-1.4	-2.0	1.4

Variable Values (mm) for "2-D Man" Model Points*

	A	B	C	D	W	X	Y	Z
Thumb Tip Reach	882.6	775.7	723.6	830.5	878.7	840.0	727.5	766.2
Buttock Knee Length	661.7	587.2	546.4	620.9	656.7	632.9	551.4	575.2
Knee Height/Sitting	609.8	533.8	505.5	581.5	611.4	577.7	503.9	537.6
Sitting Height	945.4	855.9	918.2	007.8	995.1	887.8	868.6	975.9
Eye Height/Sitting	820.8	737.2	798.2	881.8	868.6	766.3	750.4	852.7

* Locations A, B, C, and D are each midquadrant points; W, X, Y, and Z refer to the points on the principal components axes.

TABLE 6

Accommodation Analysis, 98%, 1967 Air Force Flying Personnel:
Five Variables

Variable Z-Scores for "2-D Man" Model Points*

	A	B	C	D	W	X	Y	Z
Thumb Tip Reach	2.3	-0.8	-2.3	0.8	2.2	1.1	-2.2	-1.1
Buttock Knee Length	2.5	-0.7	-2.5	0.7	2.3	1.2	-2.3	-1.2
Knee Height/Sitting	2.4	-1.1	-2.4	1.1	2.5	0.9	-2.5	-0.9
Sitting Height	0.5	-2.8	-0.5	2.8	2.3	-1.6	-2.3	1.6
Eye Height/Sitting	0.4	-2.8	-0.4	2.8	2.3	-1.7	1.7	-2.2

Variable Values (mm) for "2-D Man" Model Points*

	A	B	C	D	W	X	Y	Z
Thumb Tip Reach	895.7	771.2	710.5	835.0	891.1	846.0	715.0	760.1
Buttock Knee Length	671.1	584.4	537.0	623.7	665.4	637.6	542.7	570.5
Knee Height Sitting	618.4	529.9	496.9	585.4	620.2	581.0	495.1	534.3
Sitting Height	947.7	843.5	916.0	1020.2	1005.5	880.5	858.2	983.1
Eye Height Sitting	822.7	725.3	796.3	893.7	878.4	759.3	740.7	859.7

* Locations A, B, C, and D are each midquadrant points; W, X, Y, and Z refer to the points on the principal components axes

can only be justified after its careful consideration ...

Next, from the new coordinate system, two ellipsoids (in three-dimensional space along the new axes and symmetric about the multivariate origin) were determined. The first (Table 7) encompassed exactly 95% (n = 2299) of the USAF67 sample (and therefore disaccommodated 5%), while the second (Table 8), concentric with the first, was somewhat larger and accommodated about 98% (n = 2369) of the flyer sample. Eight multivariate points were systematically located on the surface of each of these spheroids (Figure 3). The intersection of a three-dimensional rectanguloid, (the unequal dimensions of which reflected the different variances of each of the three components,) with the surface of the spheroid, provided these points. Multivariate points can also be located at the ends of each of the major axes (as in Cases W, X, Y, Z in the 2-D analysis) to exhibit the most extreme values along each component. This would require six additional model points.

THE PROBLEM OF MULTIPLE POPULATIONS

In this section an analysis is described which addresses an altogether new type of problem: multivariate accommodation for a composite population of white male, white female, and black male flyers. Sampled anthropometric data from white males (1967), white females (1968), and black males (1965) are used in this analysis to estimate the accommodation limits of workstation anthropometrics for a hypothetical population of flyers in the 1990s. (These sample surveys will be designated "67AF white males," "68AF white females," and "65AF black males" in this report). This preliminary study presents accommodation limits (90% and 99.5%) which may be regarded as accurate and unbiased *only if* the following assumptions hold: (1) the composition of the hypothetical flyer population is one-third white males, one-third white females, and one-third black males; (2) there are no secular trends in body dimensions over the three decades separating the collection of the 1960s survey data and the application of the new standards in the 1990s; and finally (3) size requirements remain at 64" to 76" for overall stature, and at 34" to 39" for sitting height. Since the first two assumptions are certainly incorrect (and even the third may be subject to change), this part of the report must be viewed as a first approach which is merely intended to introduce the nature of an important problem. Results can be easily modified should height requirements be changed and should some estimate of the race sex composition of the population of flyers become available. Temporal changes in body dimensions must be addressed by more current surveys, such as the 1987-88 U.S. Army anthropometric survey (Gordon et al., 1988).

The critical cockpit variables for this analysis included measures of trunk height (including eye level and head height), the extension of the arm, and measurement of both the shank and the thigh dimensions of the lower limb. The three anthropometric survey populations used in this analysis were each measured for sitting height, eye height sitting, acromion height sitting, thumb tip reach, not extended, and buttock-knee length. The only measure of the shank which all three surveys included is popliteal height sitting, which in this analysis replaced knee height sitting as the sole measure of this critical dimension.

Since the general survey populations are delimited on sitting height and stature requirements from AF Regulation 160-43 to form the composite flyer population, the sample of women is most affected. The required lower bounds in sitting height and stature are each at or over the means of the original female population (Figure 4). Therefore, to meet current body size restrictions, over three quarters of this sample was necessarily deleted. Some truncation of

TABLE 7

Eleven Anthropometric Variables Reduced to Three Principal Components, 1967 Air Force Flying Personnel, Model Points at Surface of 95% Accommodation Ellipsoid
(values in mm)

COMPONENTS	A	B	C	D	E	F	G	H
Component 1 (limb elements)	+	+	+	-	+	-	-	-
Component 2 (vertical head, neck and trunk dimensions)	+	+	-	+		+	-	-
Component 3 (hand and foot lengths)	+	-	+	+	-	-	+	-

\+ = big
\- = small

Octant:	A	B	C	D	E	F	G	H
Sitting Height	999	978	910	977	888	952	886	867
Acromion Height/Sitting	669	659	583	649	572	637	565	552
Knee Height/Sitting	618	583	595	549	565	521	531	502
Buttock-Knee Length	653	630	645	584	622	564	577	558
Shoulder-Elbow Length	395	385	381	347	371	337	333	324
Elbow-Wrist Length	330	311	322	295	304	278	287	268
Biacromial Breadth	420	411	414	410	404	400	403	394
Hip Breadth	368	361	354	357	347	349	343	336
Chest Depth	253	248	250	244	245	239	241	236
Foot Length	297	265	289	282	258	252	274	243
Hand Length	210	187	204	199	182	177	194	172

TABLE 15

TABLE 8

Eleven Anthropometric Variables Reduced to Three Principal Components, 1967 Air Force Flying Personnel, Model Points at Surface of 98% Accommodation Ellipsoid
(values in mm)

Components	A	B	C	D	E	F	G	H
Component 1 (limb elements)	+	+	+	-	+	-	-	-
Component 2 (vertical head, neck and trunk dimensions)	+	+	-	+	-	+	-	-
Component 3 (hand and foot lengths)	+	-	+	+	-	-	+	-

\+ = big
\- = small

Octant:	A	B	C	D	E	F	G	H
Sitting Height	1017	992	905	989	878	957	876	849
Acromion Height/Sitting	687	673	576	661	563	645	552	539
Knee Height/Sitting	630	591	604	547	567	511	525	484
Buttock-Knee Length	668	637	656	579	627	555	571	546
Shoulder-Elbow Length	407	392	386	344	374	332	327	316
Elbow-Wrist Length	341	315	328	294	305	272	284	262
Biacromial Breadth	423	412	416	411	404	399	403	390
Hip Breadth	373	363	354	357	345	349	340	331
Chest Depth	255	249	251	244	245	238	240	234
Foot Length	306	264	294	285	255	247	275	238
Hand Length	217	186	208	202	180	174	195	168

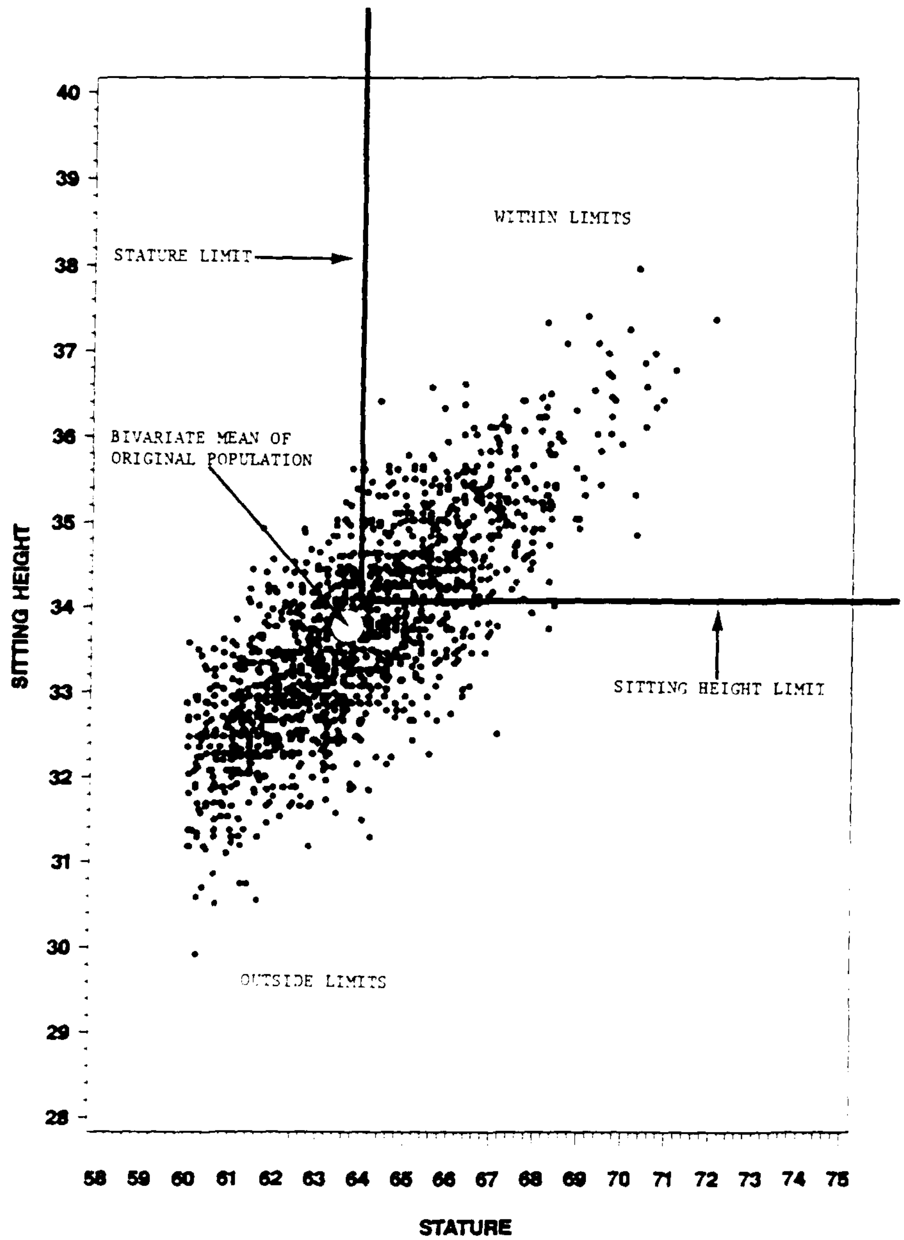

FIGURE 4

Joint Distribution of Sitting Height and Stature,
1968 Air Force White Females, Truncated

the 67AF white males and the 65AF black males also occurred. This resulted in somewhat abrupt limits to otherwise bivariate normal distributions that are visible at the lower bounds for 65AF black males (Figure 5) and especially for 68AF white females. With the exception of the selector variable (Sitting Height) these procedures only affected the shapes of the univariate distributions to a small degree. The limb lengths remain close to normal within all three populations.

The major univariate differences among the populations are: (1) the shorter reach and stature of women: (2) the very large average sitting height of white males; and (3) the longer limb lengths of black males. These differences in turn translate into large reach-to-trunk ratios and very large leg-to-trunk ratios for blacks compared to Whites. The eventual knowledge of the exact nature of the linear size differences (between sexes) and the proportional differences (between women of both races) for accommodation studies will have to await a comparable survey of black women.

The correlation matrix of the truncated, equally weighted, composite population was analyzed by means of principal components. The first component (primarily size) and the second component (relative trunk length) accounted for 84% of the original variation (Table 9). Eight surface locations were calculated for the 90% and the 99.5% accommodation ellipses (Tables 10 and 11). Figure 6 presents a distribution of the composite population in principal components space, and two accommodation ellipses, 90% and 99.5%, defined by eight model points each (Tables 10 and 11). The inner ellipse accommodates exactly 90% of the cases closest to the multivariate centroid, and excludes the other 10%; the outer one represents the boundary for 99.5% accommodation. The 8 model points of Tables 10 (90%) and 11 (99.5%) represent different kinds of extremes located exactly on--and evenly spaced about--the boundary which separates the accommodated and the disaccommodated. However, unlike the results of the previous analyses, disaccommodation is far from symmetric. First, there is the persistent problem of the abruptness of the lower limit of the distributions caused by the restrictions on sitting height. Model points Z and especially C and Y (very negative in component 1 and or component 2) represent extremes which are more abnormal than any USAF flyer in the truncated, composite population. That is, there is no reason to test flyers for such extreme anthropometrics. The sitting height (and possibly stature) requirements have already eliminated them. New single model points C* and Y* are provided for 90% and 99.5% accommodation (Tables 10 and 11). These multivariate vectors are substituted for the lower left midquadrant location (point C*) and for the lowermost location (point Y*) at all accommodation levels. Similarly, a new model point Z* (extreme left location, i.e., very negative on component 2) is provided for the 99.5% accommodation only (Table 12).

The percentage of individuals accommodated at either of the two accommodation levels is not uniform with respect to race or sex (Table 12). The women in the test sample derived for this study were almost completely accommodated in both models. However, this observation may be misleading. It should be remembered that over three-quarters of the original general female population was excluded on the basis of the stature and sitting height restrictions currently in effect for the population of Air Force pilots (Figure 4). By contrast, the truncation of any male population on the basis of the 34" to 39" sitting height requirement is not as extensive. On the other hand, no woman in this study was found to be too large in "size" (first principal component) or in the proportion of total stature that is trunk height (second principal component). Therefore, of those women whose anthropometrics were analyzed in this study, all were accommodated at the 99.5% level, and all but 1.3 percent were accommodated at the 90% level (Table 12).

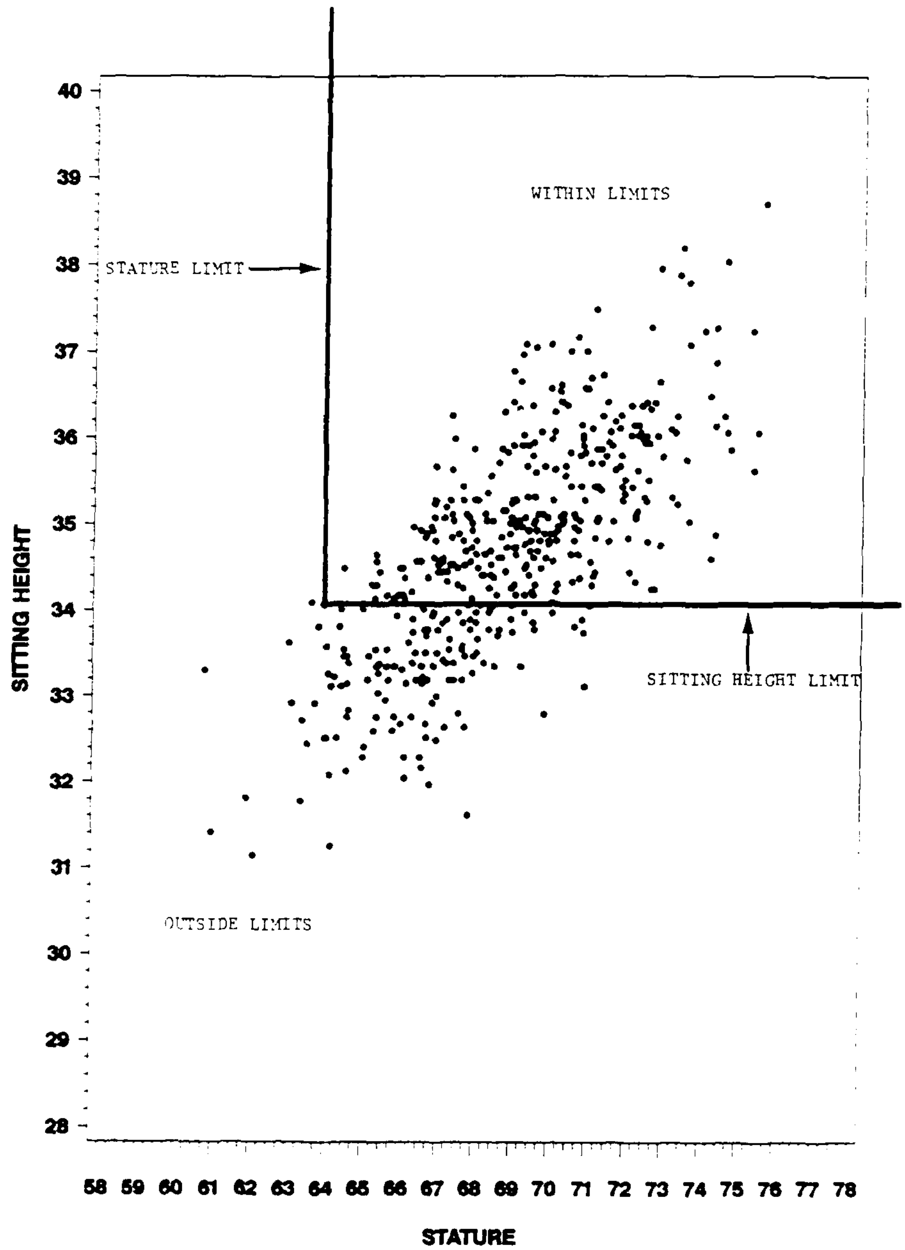

FIGURE 5

Joint Distribution of Sitting Height and Stature
1965 Air Force Black Males, Truncated.

TABLE 9

Principal Components Analysis, Composite Population, Equally Weighted, 1968 Air Force White Females, 1965 Air Force Black Males, 1965 Air Force White Males (Stature, Sitting Height, and Weight Restrictions)

Total Correlation Matrix, r_{ij}:

	Thumbtip Reach	Buttock Knee Length	Popliteal Height	Sitting Height	Eye Height/ Sitting
Buttock Knee Length	.665				
Popliteal Height	.711	.758			
Sitting Height	.248	.231	.286		
Eye Height/Sitting	.280	.267	.360	.910	
Shoulder Height/Sitting Derived	.116	.146	.134	.762	.693

Eigenvalues, (Unrotated Principal Components, λ_j) and Percentage of Variation (%):

Factors

	(1)	(2)	(3)	(4)	(5)	(6)
Eigenvalues	3.21*	1.82*	0.35	0.33	0.21	0.09
Variation	54%	30%	6%	5%	4%	1%

*Only the first two principal components were used in subsequent analysis.

TABLE 10

Accommodation Analysis, 90%, Composite Population

Variable Z-Scores for "2-D Man" Model Points

	A	B	C*	D	W	X	Y*	Z
Thumb Tip Reach	0.1	-1.8	-0.1	1.8	1.4	-1.2	-1.2	1.2
Buttock Knee Length	0.1	-1.9	-0.1	1.9	1.4	-1.2	-1.2	1.2
Popliteal Height	0.2	-1.9	-0.2	1.9	1.5	-1.2	-1.3	1.2
Sitting Height	2.0	-0.4	-1.4	0.4	1.7	1.1	-1.4	-1.1
Eye Height/Sitting	1.9	-0.6	-1.4	0.6	1.7	0.9	-1.5	-0.9
Shoulder Height/Sitting Derived	1.9	-0.1	-1.4	0.1	1.4	1.2	-1.2	-1.2

Variable Values (mm) for "2-D Man" Model Points

	A	B	C*	D	W	X	Y*	Z
Thumb Tip Reach	794.9	705.3	783.6	871.3	851.6	734.3	734.7	842.4
Buttock Knee Length	609.0	549.3	602.0	660.6	647.2	560.5	569.2	641.4
Popliteal Height	452.1	392.1	440.4	498.6	487.8	412.5	409.4	478.2
Sitting Height	950.9	889.5	863.6	911.2	943.8	928.5	863.6	872.3
Eye Height/Sitting	835.1	768.7	746.4	798.8	830.7	809.5	744.0	758.1
Shoulder Height/Sitting Derived	630.1	579.4	547.0	584.6	617.9	614.2	551.7	549.9

* Points modified from original symmetric ellipse due to sitting height restrictions: New radii, Y=1.777; New component, C=-1.079.

TABLE 11

Accommodation Analysis, 95%, Composite Population

Variable Z-Scores for "2-D Man" Model Points

	A	B	C*	D	W	X	Y*	Z
Thumb Tip Reach	0.2	-2.1	-0.1	2.1	1.6	-1.4	-1.2	1.4
Buttock Knee Length	0.2	-2.2	-0.1	2.1	1.7	-1.4	-1.2	1.4
Popliteal Height	0.3	-2.2	-0.2	2.2	1.8	-1.4	-1.3	1.4
Sitting Height	2.3	-0.5	-1.4	0.5	2.0	1.3	-1.4	-1.3
Eye Height/Sitting	2.2	-0.6	-1.4	0.6	2.0	1.1	-1.5	-1.1
Shoulder Height/Sitting Derived	2.2	-0.1	-1.4	0.1	1.6	1.5	-1.2	-1.5

Variable Values (mm) for "2-D Man" Model Points

	A	B	C*	D	W	X	Y*	Z
Thumb Tip Reach	796.0	691.5	783.6	885.2	862.2	725.3	734.7	851.4
Buttock Knee Length	609.7	540.1	602.0	669.9	654.2	562.4	569.2	647.5
Popliteal Height	453.3	383.3	440.4	507.5	494.9	407.0	409.4	483.7
Sitting Height	959.4	887.7	863.6	913.0	951.0	933.1	863.6	867.6
Eye Height Sitting	843.7	766.2	746.4	801.4	838.6	813.7	744.0	753.9
Shoulder Height Sitting Derived	638.1	579.0	547.0	585.1	623.8	619.5	551.7	544.5

* Points modified from original symmetric ellipse due to sitting height restrictions: New radii, Y=1.777; New component, C=-1.079.

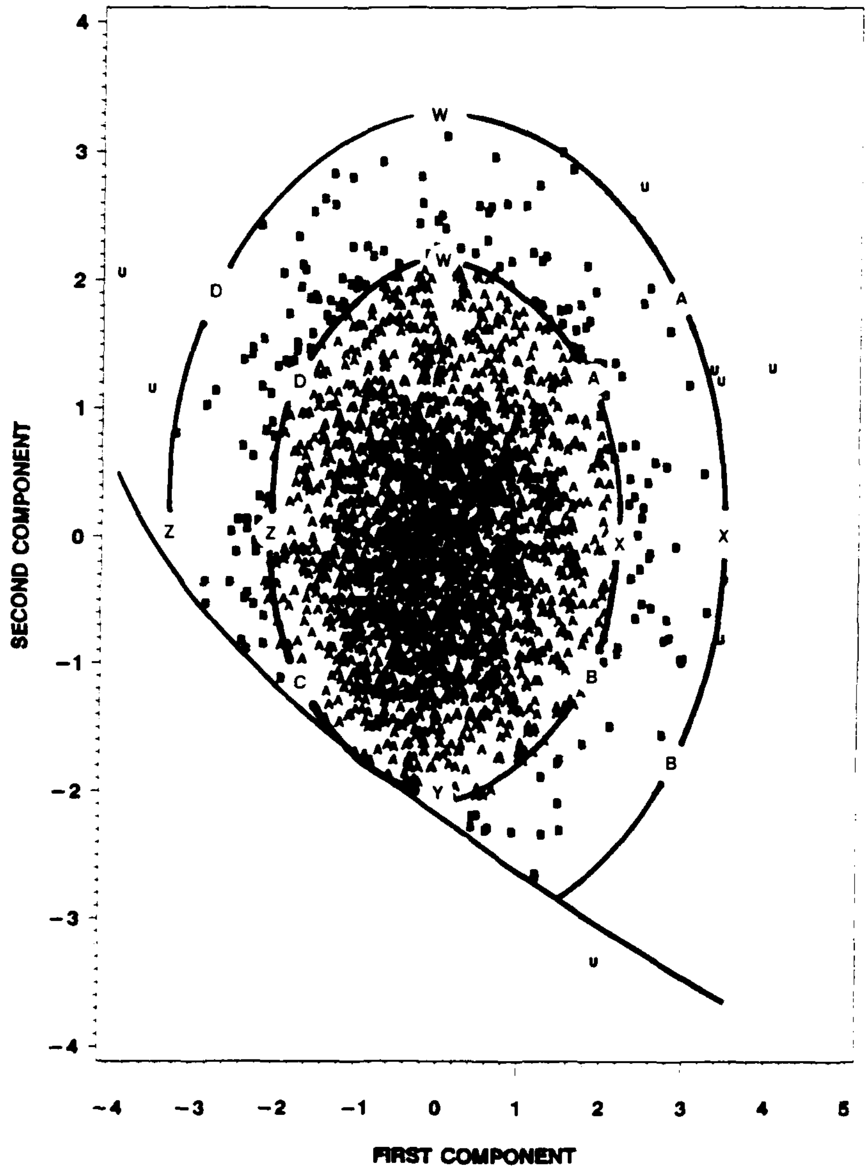

FIGURE 6

Joint Distribution of Principal Components One and Two, Accommodation Analysis, Composite Population, 90% and 99.5% Ellipses

TABLE 12

Accommodation Analysis, Within-Group
Percentages, Composite Population

Total Accommodation Within-Group Accommodation

	68AF White Women	65AF Black Males	65AF White Males
90%:	98.7%	85.7%	85.7%
99.5%:	100.0%	99.4%	99.1%

Of the population of males derived and defined for this study on the basis of the sitting height and stature restrictions, accommodation is approximately equal for both races (Table 12). However, disaccommodation is not symmetric for either male group. For the Blacks, all those who were disaccommodated at the 99.5% level were found in the upper left quadrant of Figure 6 (not all shown); that is, they had relatively small trunk lengths coupled with extremely long limbs. For the white males, *all* those disaccommodated at the 99.5% level, were located in the upper right quadrant of Figure 6; that is, they were large individuals with extremely large trunk dimensions.

To avoid the problem of differing accommodation rates for different populations it may be necessary to analyze the three populations separately and compare and combine the resulting models. The final analysis described here calculates model points for each of the three samples separately. Tables 13 through 15 show the percentile values and model points for the 68AF white females, 65AF black males, and 67AF white males at the 95% accommodation level. Comparing the A model points (long limb lengths) across the three populations, it is obvious that the black male population exhibits the most extreme limb lengths. It would be unnecessary to design or test using the white male or female model point A. Similarly, for model points C (small limbs), D (large torso), X (short torso/long limbs), Y (small all over), and Z (large torso/short limbs), the choice between the three populations is fairly obvious. However, model points B (small torso), and W (large all over) are more difficult to select. For Model B the values for Sitting Height and Shoulder Height for the female and black male are fairly close and favor selection of the black male model as smallest. However, the female model has a shorter Eye Height Sitting, which in a cockpit environment can present a more critical problem than does a short Sitting Height. For Model point W (generalized large), the white male torso is roughly 4 centimeters larger than that of the black male, but the black male has limbs roughly 4 centimeters longer than those of the white male. An inclusion of both models in an expanded set would be necessary.

TABLE 13

Two-Component Representative Cases:
White Females (95% Accommodation)

Percentile Values

	A	B	C	D
Sitting Height	80	2	20	98
Eye Height Sitting	72	2	28	98
Shoulder Height/Sitting Derived	77	4	23	96
Buttock-Knee Length	98	66	2	34
Thumb Tip Reach	96	69	4	31
Popliteal Height, Sitting	97	65	3	35

	W	X	Y	Z
Sitting Height	98	19	2	81
Eye Height Sitting	97	15	3	85
Shoulder Height/Sitting Derived	96	23	4	77
Buttock-Knee Length	87	96	13	4
Thumb Tip Reach	81	94	19	6
Popliteal Height, Sitting	87	95	13	5

TABLE 13 (cont'd)

Variable Values

	A	B	C	D
Sitting Height	90.45	85.19	87.40	92.65
Eye Height Sitting	77.85	72.54	75.52	80.84
Shoulder Height/Sitting Derived	59.17	53.90	56.09	61.35
Buttock-Knee Length	63.00	59.72	54.79	58.06
Thumb Tip Reach	81.82	77.80	70.51	74.53
Popliteal Height, Sitting	45.34	42.85	39.13	41.62

	W	X	Y	Z
Sitting Height	92.64	87.36	85.21	90.48
Eye Height Sitting	80.45	74.57	72.93	78.80
Shoulder Height/Sitting Derived	61.35	56.08	53.90	59.17
Buttock-Knee Length	61.21	62.38	56.58	55.41
Thumb Tip Reach	79.01	81.32	73.32	71.01
Popliteal Height, Sitting	44.00	44.87	40.48	39.60

TABLE 14

Two-Component Representative Cases:
Black Males (95% Accommodation)

Percentile Values

	A	B	C	D
Sitting Height	69	1	31	99
Eye Height Sitting	70	1	30	99
Shoulder Height Sitting Derived	72	2	28	98
Buttock-Knee Length	98	41	2	59
Thumb Tip Reach	98	44	2	56
Popliteal Height, Sitting	99	41	1	59

	W	X	Y	Z
Sitting Height	98	10	2	90
Eye Height Sitting	98	11	2	89
Shoulder Height Sitting Derived	97	15	3	85
Buttock-Knee Length	95	91	5	9
Thumb Tip Reach	94	91	6	9
Popliteal Height, Sitting	96	92	4	8

TABLE 14 (cont'd)

Variable Values

	A	B	C	D
Sitting Height	90.78	84.43	88.50	94.86
Eye Height Sitting	79.59	73.22	77.22	83.59
Shoulder Height/Sitting Derived	58.52	52.77	55.92	61.67
Buttock-Knee Length	68.66	61.90	56.40	63.16
Thumb Tip Reach	90.91	81.09	72.63	82.45
Popliteal Height, Sitting	52.20	46.20	41.28	47.27

	W	X	Y	Z
Sitting Height	94.14	86.76	85.15	92.52
Eye Height Sitting	82.91	75.58	73.90	81.23
Shoulder Height/Sitting Derived	61.29	54.99	53.15	59.45
Buttock-Knee Length	67.31	66.42	57.75	58.64
Thumb Tip Reach	88.71	87.75	74.83	75.79
Popliteal Height, Sitting	50.98	50.22	42.50	43.26

TABLE 15

Two-Component Representative Cases:
White Males (95% Accommodation)

Percentile Values

	A	B	C	D
Sitting Height	78	2	22	98
Eye Height Sitting	76	2	24	98
Shoulder Height/Sitting Derived	71	2	29	98
Buttock-Knee Length	98	41	2	59
Thumb Tip Reach	98	40	2	60
Popliteal Height, Sitting	98	34	2	66

	W	X	Y	Z
Sitting Height	98	16	2	84
Eye Height Sitting	98	15	2	85
Shoulder Height/Sitting Derived	97	14	3	86
Buttock-Knee Length	95	90	5	10
Thumb Tip Reach	95	90	5	10
Popliteal Height, Sitting	96	87	4	13

TABLE 15 (cont'd)

Variable Values

	A	B	C	D
Sitting Height	95.14	86.96	90.86	99.04
Eye Height Sitting	82.68	75.00	78.88	86.56
Shoulder Height/Sitting Derived	62.37	55.54	59.48	66.31
Buttock-Knee Length	65.74	59.73	54.95	60.96
Thumb Tip Reach	88.05	79.28	72.38	81.14
Popliteal Height, Sitting	48.10	42.75	39.20	44.54

	W	X	Y	Z
Sitting Height	98.78	90.24	87.22	95.76
Eye Height Sitting	86.21	78.04	75.35	83.53
Shoulder Height/Sitting Derived	65.75	58.14	56.10	63.71
Buttock-Knee Length	64.60	63.72	56.09	56.97
Thumb Tip Reach	86.41	85.09	74.01	75.33
Popliteal Height, Sitting	47.43	46.16	39.87	41.13

CONCLUSION

A preliminary attempt was made, at the conclusion of this analysis, to reduce six critical cockpit dimensions to two new measures (principal components), and to disaccommodate extreme anthropometric combinations as symmetrically as possible, while still applying the sitting height restrictions for the current population of Air Force flying personnel. It was also found appropriate to equally weight the anthropometric information of the three "derived" populations (68AF white females, 65AF black males, and 65AF white males), or to consider each population separately and combine the results. The issue of designing a workstation based on the anthropometrics of a composite user population is an important one. It requires a multivariate approach, additional survey data, and of course some reliable estimates of the actual proportions of males, females, Whites, Blacks, and others in future user populations. Depending on the extent of international application, some analysis of the anthropometrics of additional populations may also be required.

REFERENCES

Bittner, A. C., 1975, Demonstration of an Approach to Evaluate Cockpit/Aircrew Anthropometric Compatibility: Advanced Harrier Analysis, Technical Publication TP-75-31 (AV-16A). Pacific Missile Test Center, Point Mugu, California.

Bittner, A. C., R. J. Wherry, and F. A. Glenn, 1986, CADRE: A Family of Manikins for Workstation Design, Technical Report 2100.07B, Man-Machine Integration Division, Naval Air Development Center, Warminster, Pennsylvania.

Clauser, C., I. Tebbetts, B. Bradtmiller, J. McConville, and C. C. Gordon, 1988, Measurer's Handbook: U.S. Army Anthropometric Survey, 1987-1988, Technical Report NATICK/TR-88-043 (AD A202 721), U.S. Army Natick Research, Development and Engineering Center, Natick, Massachusetts.

Dillon, W. R., and Goldstein, 1984, Multivariate Analysis, John Wiley and Sons, New York City, New York.

Gordon, C.C., T. Churchill, C.C. Clauser, B. Bradtmiller, J.T. McConville, I. Tebbets and R. Walker, 1989, 1987-1988 Anthropometric Survey of U.S. Army Personnel: Summary Statistics Interim Report, Technical Report NATICK/TR-89/027 (AD A209 600), U.S. Army Natick Research, Development and Engineering Center, Natick, Massachusetts.

Harmon, H. H., 1975, Modern Factor Analysis, University of Chicago Press, Chicago, Illinois.

Korna, M., and J. W. McDaniel, 1985, User's Guide for Combiman Programs (Computerized Biomechanical Man-Model), Version 7, Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.

McConville, J. T., I. Tebbetts, L.L. Laubach, and E. Churchill (eds.), 1978, Anthropometric Source Book, Volume I: Anthropometry for Designers, NASA Reference Publication 1024 (NTS No. N79-11734), National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas.

Robinette, K.M. and J.T. McConville, February 1981, "An Alternative for Percentile Models," SAE Technical Paper Series No. 810217, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, Michigan.

Roebuck, J.A., Jr.K.H.E. Kroemer and W.G. Thomson, 1975, Engineering Anthropometry Methods, John Wiley and Sons, New York City, New York.

U S G P O 1993-750-061/81012